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Renewable Energy Transition, Energy Efficiency, and Carbon-Emission Pressure in China (1990-2022): An Open-Data Time-Series Study

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Abstract: *China's low-carbon transition is central to sustainable development because the country combines rapid economic growth, large energy demand, and fast renewable-energy deployment. This paper examines whether renewable-energy expansion and efficiency improvement reduced carbon-emission pressure in China during 1990-2022. Using open country-year data from the World Bank's World Development Indicators and Databank, it analyzes total CO_2 emissions, GDP per capita, energy use, electricity consumption, renewable final energy, low-carbon electricity shares, and primary energy intensity. The method combines descriptive statistics, indexed trend analysis, correlation analysis, and three exploratory ordinary least squares models with HAC standard errors. Results show strong relative decoupling but no full absolute decoupling. GDP per capita increased much faster than total CO_2 emissions, energy intensity declined by about 42.3 percent from 2000 to 2021, and non-hydro renewable electricity rose from nearly zero in 1990 to 12.86 percent in 2021. However, emissions still exceeded 12500 Mt CO_2e in 2022. The findings indicate that efficiency and renewable power reduced emissions pressure, but fossil displacement must accelerate to support carbon-peaking and neutrality goals.*

Keywords: *Renewable energy; Energy intensity; Carbon emissions; China; Sustainable development; Open data; Time-series analysis*

1. Introduction

Climate change has become one of the most important constraints on economic development, industrial planning, and environmental governance. The Intergovernmental Panel on Climate Change (IPCC) argues that deep, rapid, and sustained reductions in greenhouse gas emissions are needed to slow warming and limit climate risks [1]. At the same time, the global economy still depends heavily on fossil fuels, and the International Energy Agency reported that total energy-related CO_2 emissions reached a new high in 2024 [2]. These facts make energy transition not only a technical problem but also a development problem. Countries must expand access to modern energy, maintain economic competitiveness, and improve living standards while reducing emissions from electricity generation, industry, transport, and buildings.

China is a particularly important case for studying this tension. It is a large middle-income economy with a long period of rapid industrialization, a huge manufacturing base for clean energy equipment [3], an electricity system historically dominated by coal, and a policy commitment to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060 [4]. The same economy also leads global manufacturing and deployment in several clean-energy technologies, especially solar power, wind power, batteries, and electric vehicles. The key research question is therefore not whether China has expanded renewables, the historical evidence clearly shows that it has. The more difficult question is whether renewable expansion and efficiency improvement are strong enough to reduce carbon-emission pressure while the economy continues to grow.

This study addresses that question with a transparent open-data analysis. Rather than using proprietary firm-level data or complex integrated-assessment models, the paper builds a simple country-year dataset from World Development Indicators and World Bank Databank [5]. The paper examines total carbon dioxide emissions excluding land-use change, GDP per capita, energy use, electricity use, renewable energy consumption, hydropower, non-hydro renewable electricity, nuclear

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electricity, and primary energy intensity. The empirical results reveal a transition that is real but incomplete. From 1990 to 2022, China's total CO_2 emissions in the dataset increased by about 418.5 percent, while GDP per capita rose by about 1,189.8 percent. This difference suggests relative decoupling because economic output per person expanded much faster than emissions. However, absolute emissions did not decline over the full study period. A second pattern is that renewable energy in final energy consumption declined in the early industrialization period, partly because traditional biomass and other non-modern renewable uses lost relative importance as modern industrial energy demand increased. Later, modern renewable electricity expanded rapidly, especially after the 2000s. Non-hydro renewable electricity increased from 0.01 percent of electricity production in 1990 to 12.86 percent in 2021. A third pattern is efficiency improvement: primary energy intensity declined from 10.91 MJ per 2021 PPP dollar of GDP in 2000 to 6.30 in 2021, a reduction of about 42.3 percent.

The paper makes three practical contributions. First, it provides a compact, reproducible dataset for a single-country sustainability analysis. Second, it separates renewable energy in final energy consumption from renewable electricity shares, which is important because the meaning of 'renewable energy' changes over time. Traditional renewable energy in final consumption is not the same as modern solar and wind power in the electricity system. Third, it interprets regression results cautiously, emphasizing associations and policy relevance rather than claiming strong causality from a short national time series. This cautious approach is important for environmental research because many variables trend together, and simple regressions can overstate certainty when they are not supported by a stronger causal design.

2. Literature Review

The relationship between economic growth and environmental pressure has been studied through several related frameworks. The environmental Kuznets curve literature asks whether pollution rises at early stages of development and then declines after income reaches a higher level. Ahmad et al. [6] examined several variables, namely per capita carbon dioxide emissions (measured in metric tons), per capita GDP, and per capita energy consumption (measured in terms of oil equivalents), and found that certain local environmental indicators exhibited an inverted U-shaped trend, while Stern warned that the evidence is often sensitive to data, model specification, and pollutant type [7]. Carbon dioxide is especially difficult because it is closely tied to energy use, industrial structure, and infrastructure. Unlike some local pollutants, CO_2 does not automatically decline when income rises; it declines only when energy systems and production systems become less carbon intensive.

The above-mentioned clarification of the determinants of CO_2 emissions provides a useful approach. In its common form, emissions are the product of population, GDP per capita, energy intensity of GDP, and carbon intensity of energy. This identity does not estimate causal effects, but it helps researchers understand why emissions can keep increasing even when one component improves. If income and energy demand grow rapidly, efficiency gains may not be enough to reduce total emissions. Conversely, if economic activity grows more slowly or if energy intensity and carbon intensity decline quickly, emissions can stabilize or fall. This logic is directly relevant to China because the country has experienced very rapid growth in income, electricity consumption, and infrastructure investment, while also improving energy efficiency and adding non-fossil power capacity.

China-specific studies have often found a close relationship among economic growth, energy consumption, and emissions. Shang et al. [8] , for example, examined energy consumption, carbon emissions, and economic growth in China and reported long-run links between energy use and emissions. Such findings are consistent with the idea that emissions mitigation in China cannot be separated from the structure of energy demand. If heavy industry, construction materials, chemicals, and export-oriented manufacturing remain energy-intensive, total emissions can remain high even as efficiency improves in individual plants or sectors. The implication is that energy transition involves both technology substitution and structural change.

Renewable energy is central to carbon mitigation, but the literature also emphasizes that adding renewables is not identical to displacing fossil fuels. York [9] argued that alternative energy sources have historically displaced less fossil energy than simple one-for-one substitution assumptions would imply. This matters because an expanding economy can add renewables while also increasing fossil fuel consumption. In such a case, clean-energy growth contributes to lower emissions intensity, but total emissions may still rise. This idea is often described as the difference between energy transition and energy addition. The policy challenge is to make renewable energy additions large enough, flexible

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enough, and institutionally supported enough to reduce fossil generation rather than merely supplementing it.

Cross-country econometric studies generally support the idea that renewable energy can reduce CO_2 emissions when it substitutes for non-renewable energy. Ozparlak and Wang [10] exploded the nexus of energy consumption, economic growth and carbon emissions in G-20 countries during 1966–2022 via panel cointegration and Granger causality analyses. Dogan and Seker [11] similarly found that renewable and non-renewable energy play different roles in emissions models for the European Union. However, these studies also show that the estimated effects depend on income, trade openness, urbanization, and model design. Evidence from OECD or EU countries cannot be transferred mechanically to China because China's industrial structure, electricity demand growth, and policy environment differ substantially from those of high-income countries.

Energy efficiency is another important research stream. Improvements in energy intensity can reduce emissions by lowering the amount of energy required to produce each unit of output. Yet efficiency gains can be partly offset by rebound effects and by expanding production. In China, efficiency improvements have been driven by industrial upgrading, more efficient equipment, policy targets, and changes in the structure of the economy. Still, a lower energy intensity does not guarantee lower total emissions if GDP grows rapidly. This distinction is visible in the data used in the present paper: energy intensity fell sharply after 2000, but total emissions continued to rise over much of the period.

The electricity sector deserves separate attention because decarbonizing electricity can support emissions reduction in transport, industry, heating, and digital infrastructure. Electrification is beneficial for climate goals only if the electricity mix becomes cleaner. Hydropower, nuclear power, wind power, and solar power have different characteristics. Hydropower can provide large-scale low-carbon electricity but is geographically limited and sensitive to rainfall. Nuclear power offers firm low-carbon generation but faces high capital costs and long construction periods. Solar and wind can expand quickly but require grid integration, storage, demand response, and market design to manage variability. Therefore, a simple renewable share does not capture all institutional and technical conditions necessary for decarbonization.

Recent policy discussions emphasize that China has both strengths and constraints. The country has large manufacturing capacity for renewable technologies and a strong record of building infrastructure. At the same time, coal power remains important for energy security, industrial production, and local fiscal interests. China's official climate targets create a long-term direction, but implementation depends on how power markets, grid planning, industrial policy, and local incentives evolve. For this reason, empirical analysis should distinguish between relative progress and absolute emissions outcomes. A country can make impressive progress in renewable deployment and energy intensity while still needing much stronger action to achieve absolute emissions decline.

3. Data and Methodology

This study uses annual data for China from 1990 to 2022. The main source is the World Bank's World Development Indicators and Databank. The dataset was constructed from indicators that are commonly used in sustainable development, energy, and emissions research. The dependent variable in the main level models is total carbon dioxide emissions excluding land use, land-use change, and forestry, measured in million tonnes of CO_2 equivalent. The key explanatory variables are GDP per capita in constant 2015 US dollars, renewable energy consumption as a share of total final energy consumption, non-hydro renewable electricity as a share of total electricity production, hydropower as a share of electricity production, and energy intensity measured as megajoules per 2021 purchasing-power-parity dollar of GDP. Additional variables include energy use per capita, electric power consumption per capita, energy imports, and nuclear electricity share, as shown in Table 1.

The period 1990-2022 is long enough to show the major change in China's development path, but not all indicators are available for every year. Renewable energy consumption and non-hydro renewable electricity are available through 2021 in the extracted WDI table. Energy intensity is available from 2000 to 2021. The study does not impute missing values. Instead, the descriptive analysis uses all available years, and the regression models use reduced samples depending on variable availability. This design is more transparent than filling missing data with artificial estimates. The accompanying data file records all available values and missing observations.

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Table 1. Variable definitions, units, and sources

Variable	Unit	Years used	Source / note
CO_2 emissions	Mt CO_2e	1990-2022	World Bank WDI/Databank; total CO_2 excluding LULUCF
GDP per capita	Constant 2015 US$	1990-2022	World Bank WDI/Databank national accounts series
Energy use per capita	kg oil equivalent per capita	1990-2022	World Bank WDI/Databank energy-use series
Electric power consumption	kWh per capita	1990-2022	World Bank WDI/Databank electricity-use series
Renewable final energy	% of total final energy consumption	1990-2021	World Bank WDI indicator EG.FEC.RNEW.ZS; source notes identify IEA Energy Statistics
Non-hydro renewable electricity	% of total electricity output	1990-2021	World Bank WDI/Databank electricity production series
Hydropower electricity	% of total electricity output	1990-2022	World Bank WDI/Databank electricity production series
Nuclear electricity	% of total electricity output	1990-2022	World Bank WDI/Databank electricity production series
Energy intensity	MJ per 2021 PPP $ GDP	2000-2021	World Bank WDI/Databank energy intensity series

Note: Missing values were not imputed; regression samples change according to variable availability.

The paper uses three complementary empirical approaches. First, it presents descriptive statistics and endpoint comparisons. These show the scale of change and make it easier to interpret the economic meaning of the variables. Second, it creates indexed trend charts using 1990 as a base year. Indexes are useful because the variables have different units. By converting emissions, GDP per capita, and electricity use per person into comparable index values, the paper shows whether economic growth, electricity growth, and emissions growth moved at similar or different speeds. Third, it estimates exploratory ordinary least squares models. These models are not designed to prove causality. They are used to summarize conditional associations among variables and to check whether descriptive patterns remain visible after controlling for income and other energy variables.

The first regression model covers 1990-2021 and estimates the relationship between the logarithm of total CO_2 emissions and the logarithm of GDP per capita, renewable final energy share, non-hydro renewable electricity share, and hydropower share. The second model uses the shorter 2000-2021 sample because energy intensity is available only for that period. It adds primary energy intensity to the level specification. The third model is a growth-rate specification for 2001-2021. In this model, annual CO_2 emissions growth is regressed on GDP per capita growth and annual changes in energy intensity, renewable final energy share, and non-hydro renewable electricity share. The third model is useful because it reduces the influence of common long-run trends and focuses on annual changes.

The level model can be expressed as: $\ln(CO_2t) = \alpha + \beta 1 \ln(GDPpct) + \beta 2\ EIt + \beta 3\ REt + \beta 4\ NREt + \beta 5\ HYDROt + \varepsilon t$, where CO_2t is total emissions excluding LULUCF, GDPpct is GDP per capita, EIt is energy intensity, REt is the renewable share of final energy consumption, NRE is non-hydro renewable electricity share, and HYDROt is hydropower share. When energy intensity is not included because of missing early-year data, the same equation is estimated without EIt. The growth model replaces levels with growth rates or annual differences. Heteroskedasticity and autocorrelation-consistent standard errors with one lag are reported because yearly national data are likely to have serial correlation [12].

This methodology has limitations. First, the sample is small and national-level variables are highly correlated over time. As a result, regression coefficients may be unstable and should not be interpreted as precise causal effects. Second, total CO_2 emissions are influenced by factors not fully represented in the model, such as industrial structure, coal prices, infrastructure cycles, exports, local policy enforcement, and weather. Third, renewable energy indicators have different meanings. Renewable final energy includes traditional uses that may not reflect modern clean-energy technology, while non-hydro renewable electricity better captures wind and solar growth but excludes end-use renewable heat and fuels. Fourth, the analysis does not directly measure air pollution, local environmental quality, or consumption-based emissions. These limitations mean that the paper should be read as an open-data assessment of broad transition patterns rather than a complete emissions-accounting study.

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4. Results

As shown in Table 2*, t*he descriptive results show that China's economic expansion over the study period was much faster than its emissions growth, but total emissions still increased substantially. Total CO_2 emissions excluding LULUCF rose from 2,414.28 Mt CO_2e in 1990 to 12,518.68 Mt CO_2e in 2022. This is an increase of approximately 418.5 percent. Over the same period, GDP per capita rose from 917.27 to 11,830.60 constant 2015 US dollars, an increase of approximately 1,189.8 percent. Electric power consumption per capita rose from 510.62 kWh to 6112.14 kWh, showing how strongly China's development path was linked to electrification and industrial energy demand.

Table 2. Descriptive statistics for the main variables

Variable	N	Mean	Std. dev.	Min	Max
CO_2 emissions (Mt CO_2e)	33	7066.19	3635.09	2414.28	12551.86
GDP per capita (2015 US$)	33	4956.28	3481.20	917.27	11830.60
Energy use per capita	33	1532.68	658.75	740.59	2676.48
Electricity use per capita	33	2489.68	1765.05	510.62	6112.14
Renewable final energy (%)	32	20.99	8.48	11.30	33.90
Non-hydro RE electricity (%)	32	2.43	3.60	0.01	12.86
Hydropower electricity (%)	33	17.18	1.39	14.79	20.40
Nuclear electricity (%)	33	2.10	1.36	0.00	4.74
Energy intensity	22	8.64	1.70	6.30	10.91

Table 3. Selected endpoint changes

Indicator	Base year/value	End year/value	Change
CO_2 emissions	1990: 2,414.28 Mt CO_2e	2022: 12,518.68 Mt CO_2e	+418.5%
GDP per capita	1990: 917.27 constant 2015 US$	2022: 11,830.60 constant 2015 US$	+1,189.8%
Non-hydro renewable electricity	1990: 0.01%	2021: 12.86%	+12.85 percentage points
Renewable final energy	1990: 33.90%	2021: 15.20%	-18.70 percentage points
Energy intensity	2000: 10.91 MJ/$2021 PPP GDP	2021: 6.30 MJ/$2021 PPP GDP	-42.3%

Figure 1 compares these three trends using 1990 as a base year. GDP per capita and electricity consumption per capita increased far more rapidly than emissions after 2000. This is a positive sign because it means that each unit of economic output became less emissions-intensive in a broad descriptive sense. However, the emissions index still increased more than fivefold by 2022. The central interpretation is therefore relative decoupling but not absolute decoupling. China's economy became less carbon intensive relative to income, but total carbon pressure remained high because the scale of economic activity and electricity demand expanded so quickly. Table 3 presents selected endpoint changes for core economic, emissions, and energy indicators across the study period.

The energy-transition indicators show a more complex pattern than a simple story of renewable growth. Renewable energy consumption as a share of total final energy consumption was 33.9 percent in 1990, but it fell to 11.3 percent in 2011 before rising to 15.2 percent in 2021. This pattern reflects the changing composition of energy use during industrialization. Early renewable final energy shares often include traditional biomass and non-commercial energy use, while modern industrialization increases the share of coal, oil, gas, and grid electricity. Therefore, a decline in the total renewable final-energy share during early development does not necessarily mean that modern renewable power was shrinking. It means that fossil-based modern energy grew faster than traditional renewable uses and early renewable systems. By contrast, non-hydro renewable electricity provides a clearer picture of modern renewable deployment. Its share was only 0.01 percent in 1990 and remained very low through the 1990s. After the 2000s, it rose steadily and reached 12.86 percent by 2021. Hydropower remained a large low-carbon electricity source, fluctuating around 15-20 percent of electricity generation, while nuclear power rose from zero in the early 1990s to 4.74 percent in 2021. Figure 2 shows that China's low-carbon electricity transition has not depended on a single technology. Hydropower provided the early base, nuclear power expanded gradually, and non-hydro renewables became increasingly important after the 2000s.

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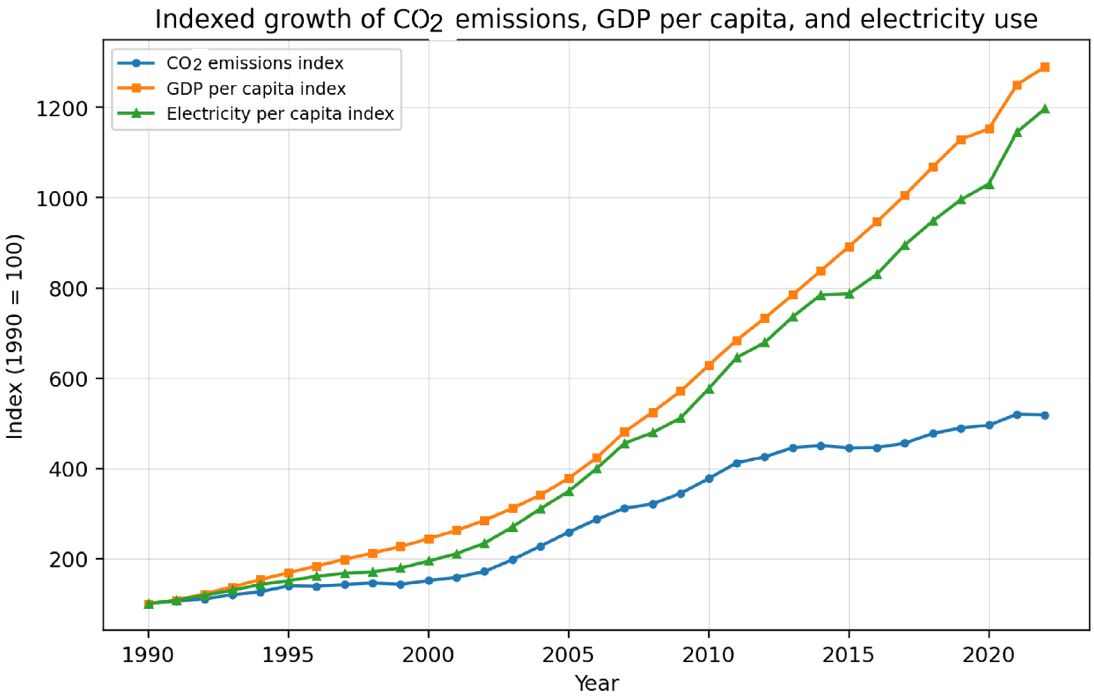

Figure 1. Indexed growth of CO_2 emissions, GDP per capita, and electricity use (1990 = 100).

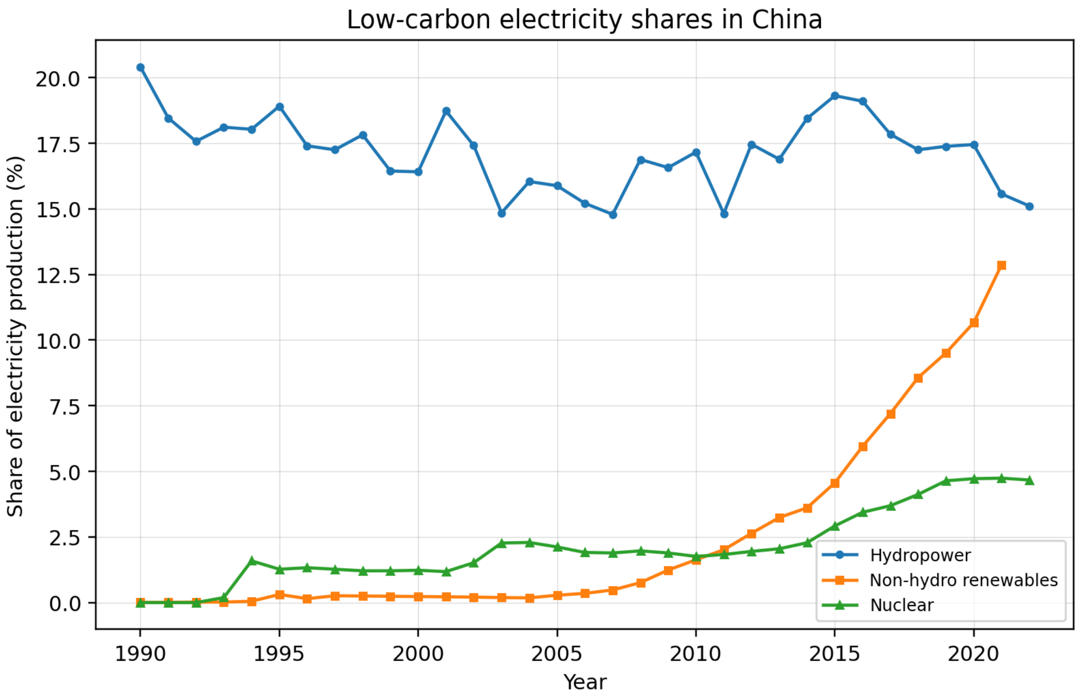

Figure 2. Low-carbon electricity shares in China, including hydropower, non-hydro renewables, and nuclear power.

Energy intensity is the strongest efficiency indicator in the dataset. It declined from 10.91 MJ per 2021 PPP dollar of GDP in 2000 to 6.30 in 2021, a reduction of approximately 42.3 percent. This means that China required much less primary energy per unit of economic output in 2021 than in 2000. Figure 3 shows the relationship between the renewable final-energy share and energy intensity. The renewable final-energy share fell in the early part of the period and then partially recovered, while energy intensity declined fairly consistently after 2000. The result suggests that energy efficiency improvement was a major factor behind relative decoupling.

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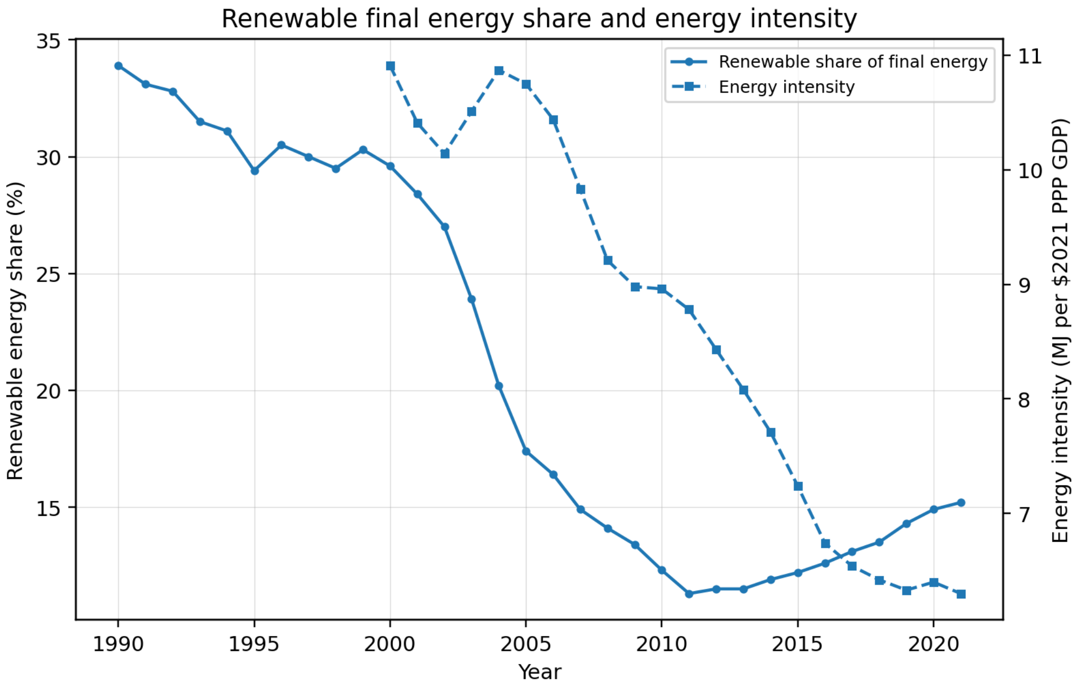

Figure 3. Renewable final-energy share and primary energy intensity.

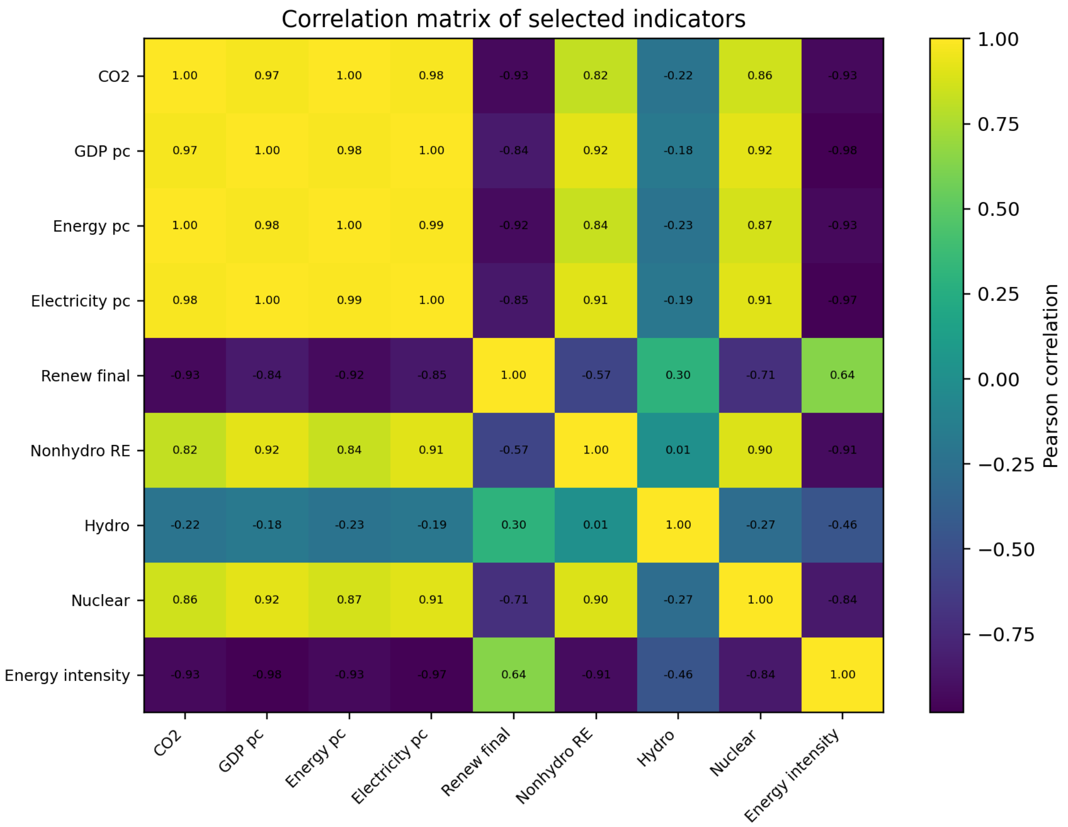

Figure 4. Correlation matrix of selected indicators. Correlations summarize co-movement and do not imply causality.

The correlation matrix in Figure 4 confirms that many variables moved together. CO_2 emissions were strongly positively correlated with GDP per capita, energy use per capita, electric power consumption per capita, non-hydro renewable electricity, and nuclear electricity. CO_2 emissions were negatively correlated with renewable final-energy share and energy intensity. These correlations need careful interpretation. The positive correlation between emissions and non-hydro renewable electricity

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does not mean renewables caused emissions to rise. It reflects the fact that both emissions and modern renewables increased during a period of rapid economic expansion. Similarly, the negative correlation between emissions and energy intensity reflects a strong downward trend in energy intensity while emissions were rising. Correlations are useful descriptions, but they do not separate causal mechanisms.

Table 4 reports the exploratory regression results. Model 1, using 1990-2021 data, shows a positive association between GDP per capita and emissions. Renewable final-energy share has a negative coefficient, while non-hydro renewable electricity has a positive coefficient in the level model. The positive coefficient on non-hydro renewable electricity is best understood as a trend and scale effect, because modern renewables rose during the same period that total electricity demand and emissions rose. Model 2, using 2000-2021 data and including energy intensity, shows that energy intensity is positively associated with emissions, while non-hydro renewable electricity and hydro-power have negative coefficients. This result is more consistent with the expectation that cleaner electricity and efficiency reduce carbon pressure after controlling for income and energy intensity. However, the model has a very high R-squared and strong multicollinearity, so the coefficients should be interpreted cautiously.

Table 4. Exploratory regression results

Term	Model 1 ln CO_2 1990-2021	Model 2 ln CO_2 2000-2021	Model 3 CO_2 growth 2001-2021
Constant	7.196*** (0.166)	-1.459* (0.728)	-0.048 (0.743)
ln(GDP per capita)	0.270*** (0.015)	1.136*** (0.073)	
GDP pc growth (%)			0.982*** (0.100)
Energy intensity		0.097*** (0.009)	
Δ Energy intensity			8.826*** (1.021)
Renewable final energy	-0.0368*** (0.0012)	-0.003 (0.003)	
Δ Renewable final energy			-1.064*** (0.279)
Non-hydro RE electricity	0.021*** (0.001)	-0.019*** (0.004)	
Δ Non-hydro RE electricity			-0.918** (0.344)
Hydropower electricity	0.000 (0.003)	-0.003** (0.001)	
Observations	32	22	21
R-squared	0.999	1.000	0.955

*Note: Standard errors in parentheses are HAC robust with one lag. Stars: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. Results are exploratory and should not be interpreted as causal estimates.*

Model 3 is the most policy-relevant specification because it examines annual changes. GDP per capita growth is positively associated with CO_2 emissions growth. A one-percentage-point increase in GDP per capita growth is associated with roughly a 0.98 percentage-point increase in emissions growth, holding the other variables in the model constant. A one-unit annual increase in energy intensity is associated with higher emissions growth, while annual increases in renewable final-energy share and non-hydro renewable electricity share are associated with lower emissions growth. The coefficients on changes in renewable final energy and non-hydro renewable electricity are negative and statistically significant in this exploratory model. This does not prove causality, but it supports the policy idea that cleaner energy shares and efficiency improvement can reduce emissions growth even when the economy is expanding.

Figure 5 shows the bi-variate relationship between GDP per capita growth and emissions growth. The scatter plot indicates a generally positive relationship, especially during the high-growth years of the early 2000s. Years such as 2003 and 2004 stand out because economic growth and emissions growth were both high. More recent years show lower emissions growth, even when GDP per capita continued to rise. This pattern is consistent with a gradual shift toward relative decoupling. It also highlights the risk of rebound: when economic activity accelerates, emissions can rise quickly unless clean-energy deployment and efficiency gains are strong enough to offset the scale effect.

Overall, the results point to three empirical conclusions. First, China achieved substantial relative decoupling between income and emissions, but not full absolute decoupling during 1990-2022. Second,

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the modern renewable electricity transition became visible after the 2000s, with non-hydro renewable electricity rising rapidly from a negligible base. Third, energy intensity improvement appears to be crucial. Without the large decline in energy intensity, emissions would likely have grown even faster. The data therefore support a balanced interpretation: China's energy transition has produced measurable progress, but the scale of energy demand and the continued role of fossil fuels mean that stronger substitution is needed for absolute emissions decline.

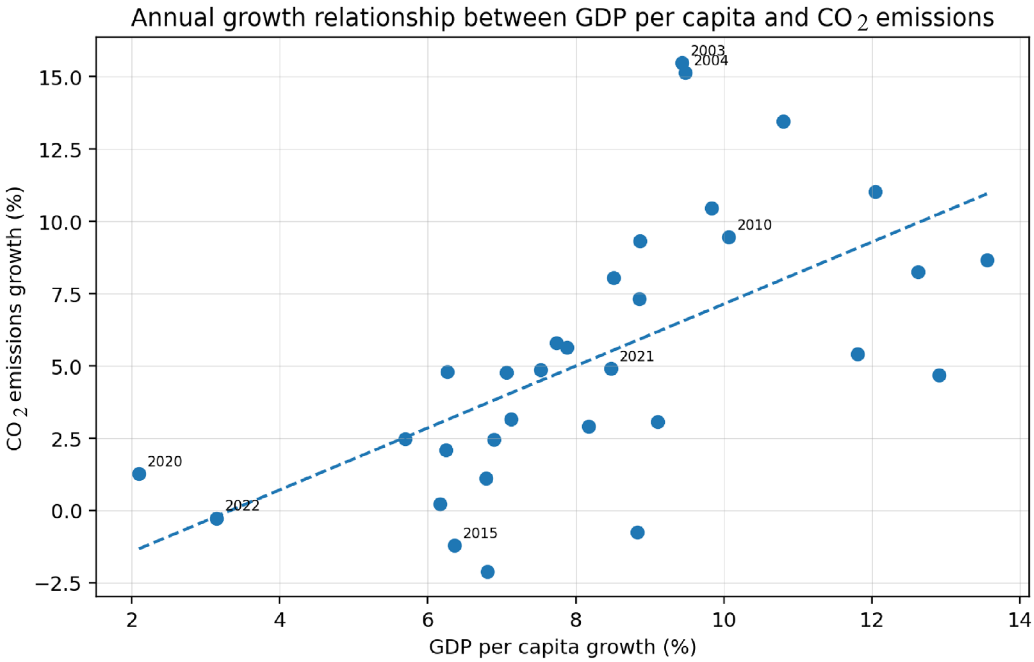

Figure 5. Annual growth relationship between GDP per capita and CO_2 emissions. Selected years are labeled.

5. Discussion

The findings have several implications for sustainable development. The first implication is that renewable expansion must be judged by fossil-fuel displacement, not only by capacity additions or renewable shares. China has made large progress in non-hydro renewable electricity, but the historical period studied here also shows how energy demand can grow so rapidly that clean-energy additions coexist with rising total emissions. This supports York's warning that alternative energy sources do not automatically displace fossil fuels one-for-one [9]. For climate policy, the key performance indicator should be how much coal and other fossil generation is actually reduced or avoided because of renewable generation, storage, demand response, and grid reform.

The second implication is that energy efficiency remains essential. Energy intensity fell substantially from 2000 to 2021, and the growth-rate regression suggests that changes in energy intensity are strongly associated with emissions growth. Efficiency policy is often less visible than solar and wind construction, but it can have large effects because it reduces the amount of energy needed across the whole economy. In China's case, industrial energy efficiency, building efficiency, appliance standards, electric-motor efficiency, and transport efficiency all matter. Efficiency also reduces the cost of energy transition because a smaller increase in electricity demand makes it easier for renewables to catch up with and displace fossil generation.

The third implication concerns the difference between relative and absolute decoupling. Relative decoupling means that emissions grow more slowly than the economy. Absolute decoupling means that emissions decline while the economy continues to grow. The data show relative decoupling but not absolute decoupling over the full 1990-2022 period. This distinction is important for evaluating progress toward carbon peaking. If policymakers focus only on emissions intensity, they may miss the fact that total emissions can still rise. For China's carbon-neutrality goal, absolute emissions reductions will eventually be necessary, especially in coal power, steel, cement, chemicals, and heavy transport.

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The fourth implication is that the electricity system is a strategic bottleneck. Non-hydro renewable electricity grew strongly, but integrating variable renewables requires more than installation. It requires transmission lines, distribution upgrades, energy storage, flexible coal operation during the transition, electricity-market reform, and demand-side management. Grid constraints can cause curtailment, while local incentives can keep fossil generation online even when renewable capacity is available. A policy strategy focused on installed capacity alone is therefore incomplete. The actual environmental effect depends on whether renewable electricity is dispatched and whether fossil generation is reduced.

The fifth implication is that hydropower and nuclear power should be interpreted carefully. Hydropower contributed a large share of low-carbon electricity throughout the period, but its share fluctuated because water availability, geography, and total electricity demand changed. Nuclear power increased gradually and can support firm low-carbon supply, but expansion speed is limited by safety regulation, capital requirements, and construction timelines. Solar and wind have grown much faster, but they are variable. A resilient low-carbon electricity system will likely require a portfolio approach: renewables, storage, transmission, nuclear, hydropower where feasible, flexible demand, and improved market incentives.

The results also relate to the Sustainable Development Goals. SDG 7 emphasizes affordable and clean energy, SDG 9 emphasizes industry and infrastructure, SDG 11 addresses sustainable cities, SDG 12 emphasizes responsible production and consumption, and SDG 13 focuses on climate action. China's experience shows that these goals interact. Industrial development and infrastructure can raise energy demand, but technological upgrading and clean-energy deployment can reduce emissions intensity. Sustainable development policy therefore needs coordination across sectors. For example, electric vehicles reduce oil demand only if the electricity system is cleaner; green hydrogen reduces industrial emissions only if produced from low-carbon electricity; and digitalization reduces emissions only if data centers are powered efficiently and cleanly.

The study also suggests several areas for future research. A more advanced analysis could use province-level data to examine regional differences in renewable deployment, coal dependence, industrial structure, and policy implementation. Province-level analysis would allow fixed-effects models and more credible identification strategies. Sectoral data would also improve the analysis because emissions from power, industry, transport, and buildings respond to different policies. Another extension would compare territorial and consumption-based emissions. China exports many carbon-intensive goods, so consumption-based accounting can change the interpretation of responsibility and policy burden. Finally, future work could use newer data after 2022 to test whether China's emissions are approaching a plateau or beginning to decline.

Despite its limitations, the present paper has value because it shows how much can be learned from transparent public data. For ordinary graduate research and domestic journal publication, a clear open-data design is often more defensible than a complicated model with unverifiable inputs. The key is to avoid over-claiming. The analysis does not prove that renewables caused emissions reductions in China. Instead, it shows that emissions growth, energy intensity, and renewable shares are related in ways that are consistent with energy-transition theory. The policy message is not that China has solved the emissions problem, but that efficiency and low-carbon electricity are measurable levers for reducing emissions pressure.

These conclusions should still be treated as indicative rather than definitive. The national time series is short, and most variables trend together, so multicollinearity can make coefficient estimates sensitive to small specification changes. The CO_2 indicator excludes land-use change, while renewable final energy mixes traditional and modern renewable uses. The study also does not include energy prices, trade, industrial composition, carbon-market design, regional differences, storage deployment, or renewable curtailment. These omissions do not invalidate the descriptive patterns, but they mean that the estimates should guide discussion rather than serve as exact policy simulations. Future research could test the same argument with province-level panels, sectoral emissions inventories, and post-2022 observations, which would allow more credible identification of when clean-energy growth becomes actual fossil-fuel displacement.

6. Conclusion

This paper examined China's renewable-energy transition, energy efficiency, and carbon-emission pressure from 1990 to 2022 using open data from the World Bank's World Development Indicators and Databank. The analysis combined descriptive statistics, indexed trends, correlation analysis, and

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exploratory OLS regressions with HAC standard errors. The results show that China's economy experienced strong relative decoupling: GDP per capita increased much faster than total CO_2 emissions. However, total emissions still rose significantly, meaning that absolute decoupling was not achieved over the whole study period.

The evidence shows that the transition has two sides. On the positive side, energy intensity declined sharply, and non-hydro renewable electricity expanded from a negligible share to a meaningful part of the electricity mix. These trends are consistent with China's policy emphasis on energy efficiency, renewable deployment, and long-term carbon neutrality. On the negative side, total emissions remained high because economic scale, electricity demand, and fossil-fuel dependence continued to grow. The early decline in renewable final-energy share also shows why renewable indicators must be interpreted carefully: traditional renewable energy and modern renewable electricity are not the same phenomenon.

The policy conclusion is that China's carbon transition depends on the speed at which clean-energy growth becomes fossil-fuel displacement. This requires more than building renewable capacity. It requires grid flexibility, storage, market reform, industrial efficiency, electrification of end uses, coal-power management, and a policy framework that rewards actual emissions reductions. Energy efficiency should remain a priority because it lowers the amount of energy that renewables must supply to displace fossil fuels. If efficiency gains slow while electricity demand continues to expand, renewable deployment will need to accelerate even faster to achieve absolute emissions decline.

For future research, the most important improvements are more detailed regional and sectoral data, stronger causal identification, and updated post-2022 observations. Province-level studies could reveal whether renewable-rich regions reduce coal generation or whether renewable additions are absorbed by new demand. Sectoral analysis could distinguish power-sector progress from industrial emissions challenges. Consumption-based accounting could also show how trade affects China's apparent emissions burden. Even with these limitations, the present open-data study supports a clear conclusion: China has made substantial progress in relative decoupling and renewable electricity expansion, but its sustainability challenge remains the conversion of technological and efficiency progress into sustained absolute emissions reductions.

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